Incentive Design for Voltage Optimization Programs for Industrial Loads

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***Abstract*—This paper presents a novel framework for planning and investment studies pertaining to the implementation of system-wide conservation voltage reduction (CVR). In the CVR paradigm, optimal voltage profiles at the load buses are determined so as to yield load reductions and hence energy conservation. The system modifications required to operate at such voltages is known to be capital intensive, which is not desirable by investors. Hence, the proposed model determines the system savings and the appropriate price incentives to offer industries such that a minimum acceptable rate of return (MARR) is accrued. In this model, the industrial facilities are represented by a combination of constant impedance, constant current, and constant power loads. A detailed case study for Ontario, Canada, is carried out considering that industrial loads are investing in voltage optimization to reduce their energy costs. The optimal incentives that need be offered by the system planner, over a long-term horizon and across various zones of Ontario, are determined using the presented mathematical model. Furthermore, a comprehensive risk analysis, comprising sensitivity studies and Monte Carlo simulations, is carried out considering the variations in the most uncertain model parameters.**

***Index Terms*—Conservation voltage reduction, voltage optimization, demand side management, incentive design, power system planning.**

NOMENCLATURE

Indices

i, j Index of bus
y Index of year

Parameters

a, b, c Constants associated with load model
d Discount rate [%]
B_{ij}^y Suceptance [pu]
G_{ij}^y Conductance [pu]
$\overline{GC_i^y}$ Maximum generation capacity [MW]
$\underline{GC_i^y}$ Minimum generation limit [MW]
$\overline{P_{ij}^y}$ Maximum line limit [MW]
${P_{ind}}_i^y$ Nominal active power of industrial load [MW]
${P_L}_i^y$ Non-industrial load [MW]
N Total number of buses
${V_o}_i^y$ Nominal voltage [pu]
Y Total number of years
ρ Electricity price [$/MWh]
β Project cost [$/MW]

Variables

I_i Investment amount [$]
IRR_i Internal rate of return [%]
J System savings [$]
P_{ij}^y Active power line flow [MW]
${P_G}_i^y$ Generator active power [MW]
${P_{ZIP}}_i^y$ Effective active power [MW]
${Q_G}_i^y$ Generator reactive power [MVAR]
${Q_{ZIP}}_i^y$ Effective reactive power [MVAR]
R_i^y Total incentive [$]
S_i^y Energy cost savings [$]
V_i^y Adjusted voltage [pu]
α Incentive [$/MWh] (control variable)
θ Power factor angle [rad]
δ_{ij}^y Angle between bus i anad j [rad]

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I. INTRODUCTION

ENERGY conservation and demand side management (DSM) are popular initiatives to dampen the growing energy demand, which may lead to increased carbon emissions, and the high cost of expanding the required power system infrastructure. Power system planners promote DSM by developing programs and incentive schemes that would invoke customers to reduce or shift their demand, so that power system upgrades can be deferred and environmental impacts can be reduced. In this context, an erstwhile but still effective energy conservation technique called conservation voltage reduction (CVR) is often used [1], which relies on the concept that, since loads are voltage dependent, operating at a load voltage close to the lower acceptable limit can reduce the energy consumption. However, operating at the lowest acceptable voltage is not always favored, for example, in display devices [2], and in motors operating at higher than rated torque conditions [3]. Finding and operating at the load voltage that has the most demand reduction, while respecting the operational constraints of the load, is referred to as voltage optimization.

In [3], a survey on the effectiveness of CVR on active power, reactive power, and energy reduction is presented, covering the period from 1941-1979, for residential, commercial, and industrial loads. In addition, experimental results presented for an induction motor with lowered voltage depict that there is a reduction in active power, with efficiency and power factor improvement. In [4], optimal power flow (OPF) based volt/var controls are proposed to optimally schedule generator voltages and transformer taps in the transmission system such that line losses are minimized. To reduce the computation time, a quadratic programming based OPF is implemented, converting an inequality-constrained model to an equality-constrained one where linear equations are solved directly. Results from the application of CVR in the Northeast Utility system are shown in [5], which involved reducing the voltage spread from 123-114 V to 120-114 V; an economic analysis demonstrates the cost effectiveness of CVR for each transformer bank tested. From the analysis, assuming that energy cost savings continue for 25 years, only one out of the eight locations tested, is found to be cost effective, implying that even with savings, CVR is capital intensive. A similar study in [6] reports that energy reduction from CVR implementation is significant and that the costs of implementation could be recovered by adding an additional fee to the customer's electricity bill. In [7], a supply curve relating the price of region-wide CVR implementation to energy savings in the Pacific Northwest is created; using this curve, the additional fee to customers over 30 years could be determined based on the desired amount of energy savings.

It should be mentioned that utilities incur reduced energy sales because of CVR, however, it also helps defer expenses on new infrastructure for utilities [8]. For example, in Ontario, a fixed rate for energy is used by utilities to charge their customers, resulting in losses to them when implementing CVR programs. In addition, utilities in Ontario are also mandated to achieve energy and peak reduction targets [9], [10]. To reconcile the loss of revenue from lower energy sales, the Ontario Energy Board (OEB) provides incentives based on their performance in meeting their reduction targets [10]. Modeling the incentives that are already offered by regulatory bodies is beyond the scope of this paper, since these vary from region to region. Instead, the intention of this paper is to present a generic model that determines the energy cost savings and the required incentive for wide-scale CVR from the perspective of the power system planner and industrial loads that are investing in CVR equipment.

The effectiveness of CVR in industrial loads is examined by analyzing the effects of voltage reduction in transformers, power supplies, lights, and ac motors in [11]. In a study by the US Department of Energy [2], twenty-four prototype feeders are modeled with physical and composite load models while matching the demand profile obtained from SCADA data without CVR. Following this modeling, CVR is applied on the feeders and the results are extrapolated on a national level by selecting the feeder types. It is noted that the feeders that are heavily loaded and allow for the most voltage reduction are the best candidates for CVR. A similar study on CVR is presented for the Australian residential sector in [12], determining the amount of loads and categorizing them as constant resistance, constant current, constant power and constant energy loads. The load category and feeder resistance is used to find the net energy savings, and sensitivity analysis is carried out varying voltages, line resistance and load ratios to determine the effect on energy savings. In Ontario, the system operator has carried out voltage reduction tests which have resulted in a 1.5% and 2.6% load reduction for a 3% and 5% reduction in voltage, respectively [13]; furthermore, during emergency operating conditions or when there is generation deficiency, the operator also uses this mechanism to reduce demand [14]. However, for system security reasons, voltage variations beyond 5% have not been considered.

Better efficiency and energy savings in the system can be achieved through voltage optimization with appropriate system modifications; however, this can be capital intensive, which is not desirable for an investor. The costs come from equipment such as a central core unit that sets the optimal voltages, voltage regulator controllers, and power monitors [15]. On the other hand, the costs accrued by a distribution system to accommodate for low operating voltages come from adding regulators or re-conductoring the feeders [1]. The benefit of voltage optimization is that it reduces energy and peak demand charges to customers. Peak demand reduction can also lead to benefits to the power system by way of deferral of capacity investments in new generation and transmission infrastructure. However, this paper only focuses on energy cost savings associated with voltage optimization and developing proper models for these studies from the system planners point of view, while considering peak demand as an implicit additional benefit from the implementation of CVR. In the event that energy cost savings cannot recover the cost of a voltage optimization implementation project for the load, financial incentives need be offered by the system planner to help investors see an appropriate rate-of-return. In this case, a system-wide mathematical model could be developed, as proposed in this paper, to determine energy cost savings in the system and the financial incentives, since it has been widely used in DSM programs (e.g. [16], [17], and [18]), from a power system planner's perspective.

Very little work has been reported in the literature on how an investor can recover costs in the context of CVR programs. In fact, it is mentioned in [3] that CVR regulatory programs have not been implemented because of the large capital investment required to prepare a system for voltage regulation, and because energy savings are uncertain. To date, there are no programs designed to induce wide-scale voltage optimization; therefore, the objective of this paper is to present a mathematical model that assists in the planning of wide-scale implementation of CVR, considering the associated equipment costs for loads. The proposed model determines the total energy cost savings, the incentives to distribute, the internal rate-of-return (IRR) for the customer from the investment, and the optimal voltages at which to operate. Although there are important considerations pertaining to the distribution system associated with CVR such as the settings for transformer taps, voltage regulators, capacitor banks and other equipment, this paper focuses on the impact of CVR on the transmission system from the system planners perspective and as such, distribution feeders and customer demands are modeled as aggregated loads at the main transmission system buses, as it is customary in these types of studies.

The rest of the paper is organized as follows: Section II describes the proposed voltage optimization model. Section III discusses the Ontario, Canada, power grid model, which is used as a realistic application of the proposed model, and presents the results as well as sensitivity analysis and Monte Carlo simulation. A summary of the presented work and the main contributions of this paper are discussed in Section IV.

II. Mathematical Modeling Framework

A. Load Representation

A generic industrial load can be represented as a combination of different voltage dependent loads that are constant impedance (Z), constant current (I) and constant power (P) [1]. Such a ZIP load can be mathematically expressed as:

$$P_{ZIP}{}_i^y = P_{ind}{}_i^y \left[a + b\left(\frac{V_i^y}{V_{o}{}_i^y}\right) + c\left(\frac{V_i^y}{V_{o}{}_i^y}\right)^2 \right] \quad (1)$$

$$Q_{ZIP}{}_i^y = P_{ZIP}{}_i^y \tan\theta \quad (2)$$

where $a+b+c=1$ and $P_{ind}{}_i^y$ represents the nominal power consumed by the load when there is no voltage adjustment and the nominal voltage ($V_{o}{}_i^y$) is 1 pu. The effective power of the load after voltage adjustment is given by $P_{ZIP}{}_i^y$, where V_i^y is the voltage that varies the effective power of the industrial load. $Q_{ZIP}{}_i^y$ can be calculated from (2) using the power factor angle θ, assuming it is constant. In this study, a variety of weights for a, b and c are used to represent industrial loads. Each set of weights, referred to as a ZIP model, is assumed to be uniform throughout the power system at each bus.

The reduction in power consumption for a ZIP load, vis-à-vis a constant power industrial load, is given by:

$$Load\ Reduction = \frac{P_{ind}{}_i^y - P_{ZIP}{}_i^y}{P_{ind}{}_i^y}\% \quad (3)$$

B. Voltage Optimization Planning Model

The savings accrued to the power system planner is the energy cost savings minus the incentives distributed. In the proposed voltage optimization planning model, the net present value (NPV) of the planner's savings, referred to as the system savings, is considered as the objective function for maximization, as follows:

$$J = \sum_{y=1}^{Y}\sum_{i=1}^{N}(S_i^y - R_i^y)\frac{1}{(1+d)^y} \quad (4)$$

As seen from (4), the system planner benefits when voltage optimization customers maximize their energy cost savings and the incentive is minimized.

It is assumed that the implementation cost depends on the electrical size of the system. Hence, the investment from industries is given by:

$$I_i = \beta\ P_{L}{}_i^1 \quad (5)$$

where the industrial demand at bus i in year 1, which is considered as the size of the system, is multiplied by the project cost β in order to determine the cost of the investment. This is a simplifying assumption in light of the available information, which may not be the actual case.

The total energy cost savings from industrial loads at bus i, over a year (8760 hours), is given by:

$$S_i^y = 8760(P_{ind}{}_i^y - P_{ZIP}{}_i^y)\rho \quad (6)$$

and the total incentive offered by the system planner to industrial customers at bus i, over a year, is given by:

$$R_i^y = 8760(P_{ind}{}_i^y - P_{ZIP}{}_i^y)\alpha \quad (7)$$

A benchmark that investors, or voltage optimization customers in this case, use to see if a project is worth pursuing is the IRR, which is a calculated interest rate at which the NPV of all cash flows equals zero; a higher value of IRR is more desirable for an investor [19]. The IRR of investors in voltage optimization at bus i is obtained by equating the NPV of both the energy cost savings and the incentive amount to the investment as follows:

$$I_i = \sum_{y=1}^{Y}(S_i^y + R_i^y)\frac{1}{(1+IRR_i)^y} \quad (8)$$

By finding the IRR, the system planner has a better insight into the zone (or bus) where investments made would result in the most benefits to industrial customers. The IRR for industrial customers at bus i is constrained by the minimum acceptable rate-of-return (MARR) as follows [19]:

$$MARR \leq IRR_i \quad (9)$$

This ensures that the IRR in each zone experiences at least the MARR in order to recover the investment in voltage optimization implementation costs.

The impact on the power system must be considered when many facilities optimize their voltage by incorporating the following power flow equations:

$$P_{G}{}_i^y - (P_{L}{}_i^y + P_{ZIP}{}_i^y) = \sum_{j=1}^{N} V_i^y V_j^y (G_{ij}^y cos\,\theta_{ij}^y + B_{ij}^y sin\,\theta_{ij}^y) \quad (10)$$

$$Q_{G}{}_i^y - (Q_{L}{}_i^y + Q_{ZIP}{}_i^y) = \sum_{j=1}^{N} V_i^y V_j^y (G_{ij}^y sin\,\theta_{ij}^y - B_{ij}^y cos\,\theta_{ij}^y) \quad (11)$$

In these equations, the aggregate load at every bus in the power system comprises both non-industrial and industrial customers. The non-industrial loads $P_{L}{}_i^y$ and $Q_{L}{}_i^y$ are represented simply by constant power loads, while the industrial loads $P_{ZIP}{}_i^y$ and $Q_{ZIP}{}_i^y$ are represented by voltage dependent loads as per (1) and (2). It should be mentioned that industrial customers that have invested in voltage optimization equipment are modeled as voltage dependent loads in this study, whereas rest of the loads are modeled as constant power loads, which are independent of voltage variations. This implicitly assumes that additional equipment such as voltage regulators and controls are in place at some of the industrial loads to reduce energy consumption, independent of the distribution system voltage levels and controls.

To ensure that line flows do not go beyond limits, the following constraint is applied:

$$|P_{ij}^y| \leq \overline{P_{ij}^y} \tag{12}$$

The voltage limits are given by:

$$0.95 \leq V_i^y \leq 1.05 \tag{13}$$

and the generation limits are given by:

$$\underline{GC_i^y} \leq P_{G_i^y} \leq \overline{GC_i^y} \tag{14}$$

The proposed voltage optimization planning model given by (1)-(14) is a non-linear programming (NLP) model that is coded in GAMS, a high-level modeling platform, and is solved using the solver MINOS [20]. With this solver, the proposed model was solved within seconds in all cases. Since this is a planning problem, and not a real-time operational problem, there is more flexibility in computational time.

III. Results and Analysis

A. Case Study Description

Ontario's grid, the system of interest for this study, comprises 10 zones: Bruce, West, Southwest (SW), Niagara, Toronto, East, Ottawa, Essa, Northeast (NE), and Northwest (NW) [21]. The simplified 10-bus power system model of Ontario shown in Fig. 1, representing these main transmission zones, is used here, since this is an adequate model for long-term planning studies as reported in [22], [23], [24]; the bus numbers correspond to the zone numbers in the simulations. The line data and line and generation limits are obtained from [24].

For this study, zonal demand and forecast data from [25] is adjusted to closely reflect the actual average demand provided in [21]. Figure 2 shows the zonal demand of Ontario, covering the period from 2011 to 2020. The share of industrial load per zone, provided in [25], is used to find the zonal industrial demand as illustrated in Fig. 3, where the industrial demand in Bruce is lumped with SW, as per [25]; Toronto has the highest industrial growth followed by SW, while East and NW are zones with the least industrial growth.

The list of nominal values input into the optimization model for the Ontario case study are summarized in Table I. The average of the Hourly Ontario Electricity Prices (HOEP) for all hours from 2002 to 2012 is obtained from [26], and that is used here as the base electricity price for the studies. The project cost is an estimate based on results presented by a voltage optimization equipment vendor [15]. The discount rate is based on the recommended value by the Treasury Board of Canada Secretariat [27], the MARR for the investor is assumed to be 10%, and the project lifetime is assumed as 10 years.

Since the ZIP load parameters in (1) are not known for the Ontario system, the following weights are considered: 1 for high, 2/3 for medium and 1/3 for low. All the specific combinations of weights that sum to one, as well as the corresponding load reduction calculated using (3), considering the load voltage as 0.95 pu, are shown in Table II.

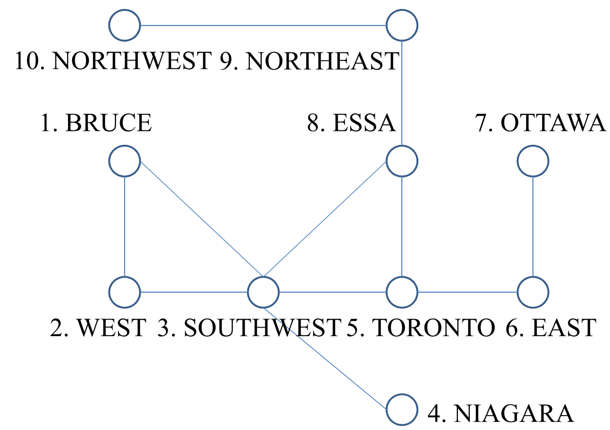

Fig. 1. Ontario 10-bus system [24]

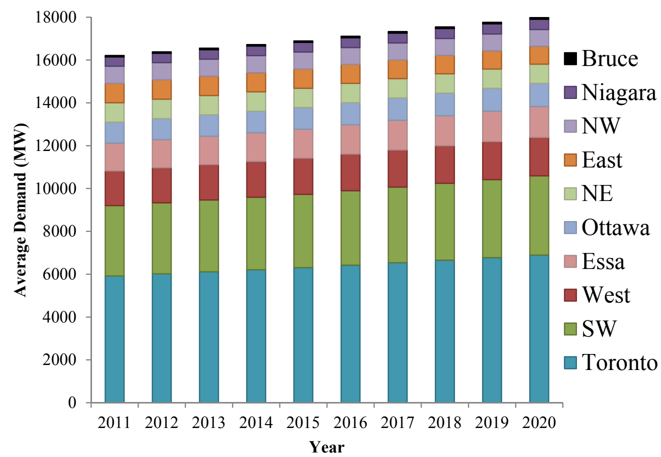

Fig. 2. Average demand estimate in Ontario for 2011 to 2020.

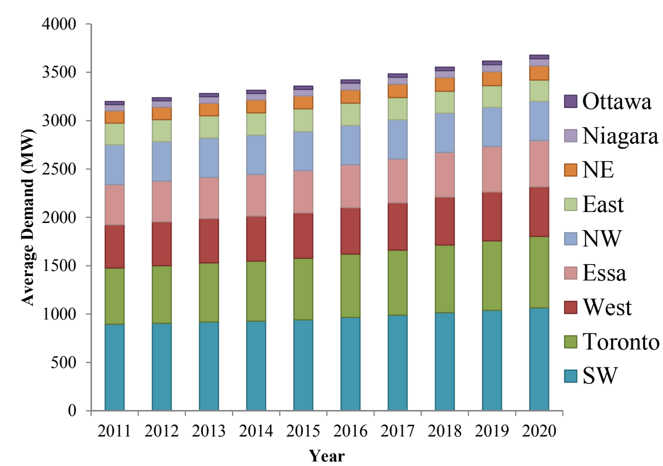

Fig. 3. Average industrial demand estimate in Ontario for 2011 to 2020.

TABLE I
BASE VALUES

Parameter	Base Value
Electricity Price	44 $/MWh
Project Cost	35 000 $/MW
Discount Rate	8%
MARR	10%
Project Lifetime	10 years

TABLE II
ZIP PARAMETERS USED FOR SIMULATIONS

ZIP Model	a	b	c	Load Reduction (%)
1	1	0	0	0.00
2	2/3	1/3	0	1.67
3	2/3	0	1/3	3.25
4	1/3	2/3	0	3.33
5	1/3	1/3	1/3	4.92
6	0	1	0	5.00
7	1/3	0	2/3	6.50
8	0	2/3	1/3	6.58
9	0	1/3	2/3	8.17
10	0	0	1	9.75

B. Base Cases

The ten base case results corresponding to the ten ZIP models, including the system savings and average zonal IRRs, are presented in Table III. The energy cost savings from the ZIP models result in IRRs that are higher than the MARR; hence, the system planner does not have to offer any incentives. The bus voltages at all zones, except Bruce, are at the minimum allowable of 0.95 pu, since it yields the maximum load reduction. The voltage at Bruce is not affected because there is no voltage optimization investment in this zone.

The case with ZIP model 2 is analyzed in detail by observing the cash flow of the system planner, as illustrated in Fig. 4. This ZIP model is used here as a reference, since it reflects the savings observed in actual CVR deployment [3]. In this figure, the system savings increase over the years as industrial demand increases. The NPV of the system savings is $146 million with ZIP model 2, and the average IRR for all zones excluding Bruce, since there is no investment in this zone, is obtained as 13.79%.

The IRR for all zones and ZIP models considered are plotted in Fig. 5. They are higher for those ZIP models which have higher load reduction; therefore, the highest IRRs are accrued from voltage optimization investments in Toronto, SW, and West, while the least correspond to Ottawa, East, and NW. It is noted that the order of zonal IRRs are directly correlated to the growth in industrial demand of the zone, i.e., the higher the growth, the higher the energy cost savings, and hence the higher IRRs from the investment. This is consistent for all ZIP models.

C. Risk Analysis using Parameter Sensitivities

A single set of results is inadequate to formulate long-term policies on incentive designs for a system planner, since parameters such as electricity price, project cost, industrial demand and discount rate are volatile. Therefore, a risk analysis is carried out considering parameter sensitivities to understand the volatility of the outcomes with respect to the

TABLE III
BASE CASE RESULTS FOR VARIOUS ZIP MODELS

ZIP Model	System Savings ($ in millions)	Average IRR (%)
1	-	-
2	146	13.79
3	284	34.66
4	291	35.67
5	430	54.09
6	437	55.59
7	568	71.80
8	575	72.00
9	714	90.17
10	852	106.48

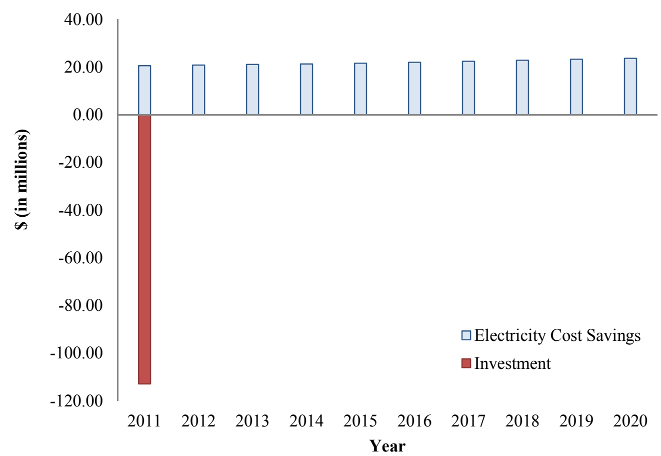

Fig. 4. Cash flow for ZIP model 2.

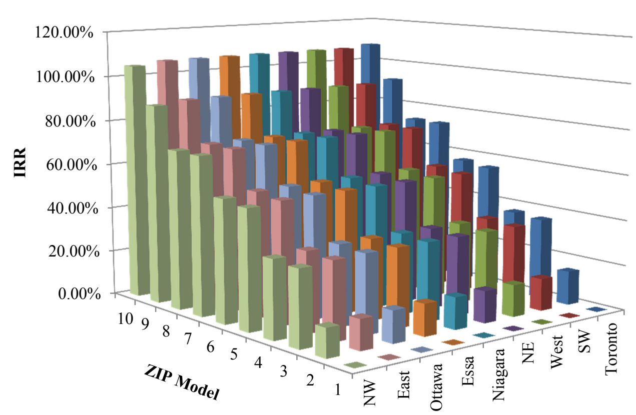

Fig. 5. Zonal IRR for each ZIP model.

parameter variations.

Although there are ten ZIP models, only ZIP model 2 is analyzed further since it is the only model that requires an incentive when parameters are varied, and is the more ”realistic”. Sensitivity analysis is performed by perturbing one parameter at a time while keeping other parameters unchanged, and analyzing the impact on the variable of interest. The variables studied are the system savings, incentive, and the IRR. Electricity price, project cost, industrial demand, and discount rate, which are the most volatile parameters, are varied by $\pm 25\%$ from their respective nominal values (Table I), while the output is plotted on a scatter plot. The sensitivity of the system savings and the incentive when each parameter is perturbed is illustrated in Fig. 6 and Fig. 7, respectively. The following observations can be made from the studies:

- As the electricity price increases, the system savings increase, as shown in Fig. 6, which is understandable, since for the same megawatt-hour reduction in energy consumption, energy cost savings are greater with a higher electricity price. When the electricity price ranges between -25% to -10% of the nominal in Fig. 6, the system savings increase at a faster rate because the corresponding incentive decreases, as shown in Fig. 7. For electricity price variation beyond -10%, the savings increase at a slower rate because the incentives are no longer offered. It should be mentioned that the base electricity price considered for this study is only a part of the electricity tariff that industrial customers in Ontario have to pay in practice, while the global adjustment factor and peak demand charges have not been considered. If these components were also considered, the resulting higher electricity price would further increase the system savings (Fig. 6), as well as reduce the required incentive rate (Fig. 7) and increase the IRR (Fig. 8). Therefore, the savings obtained in these studies are “pessimistic” estimates, and peak demand charge and global adjustment factor would only make voltage optimization implementation more desirable to an investor.
- The project cost does not impact the system savings from -25% to 10%, as seen in Fig. 6. Beyond 10% variation of the project cost, the system savings decrease because of the introduction of incentives, as shown in Fig. 7. This is an expected result since as the cost of the system increases, incentives are required.
- As the industrial demand increases, the system savings increase proportionately, as shown in Fig. 6. The more participation in voltage optimization, the higher the system savings, which is a desirable result for the system planner.
- As the discount rate increases, the system savings decrease because the later year savings are discounted more. The incentive is unaffected by changes in the industrial demand and the discount rate; hence, they are not shown in Fig. 7.

Instead of showing the IRR for every zone as obtained from the optimization model, the average IRR is used to carry out the sensitivity analysis, as shown in Fig. 8. From this figure, the following can be noted:

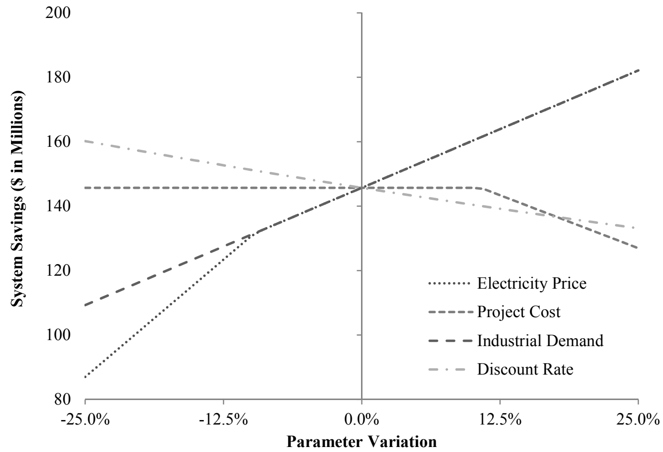

Fig. 6. Sensitivity analysis for system savings with ZIP model 2.

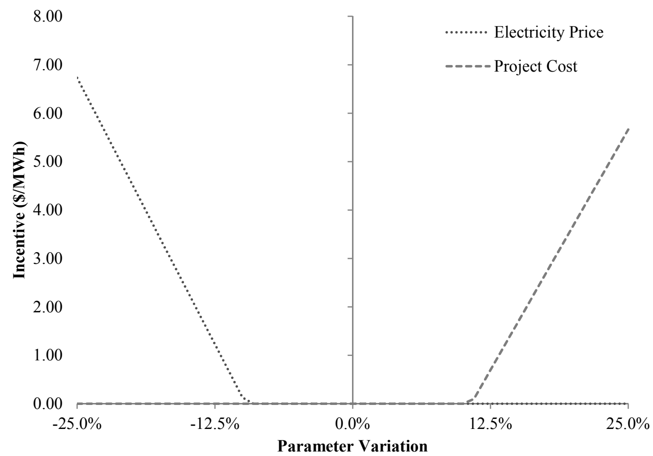

Fig. 7. Sensitivity analysis for incentive with ZIP model 2.

- For variations of the electricity price in the range of -25% to -10%, the IRR remains at 10% because of constraint (9), which prevents the IRR to dip below the MARR. Beyond that, the IRR increases with increasing electricity price because of the corresponding increase in system savings, as noted in Fig. 6. This is due to the high return on investment accrued when the electricity price increases.
- From a -25% to 10% variation of the project cost, the IRR decreases; beyond 10%, the IRR saturates close to 10% because of constraint (9). As the project cost increases, the IRR decreases because it is more difficult for the investors to recover their costs with higher project costs.
- The IRR is independent of the industrial demand and the discount rate.

For sensitivity analysis, it is customary to vary parameters over a certain range from their nominal values and to study the impact of the variation on the variables of interest, which

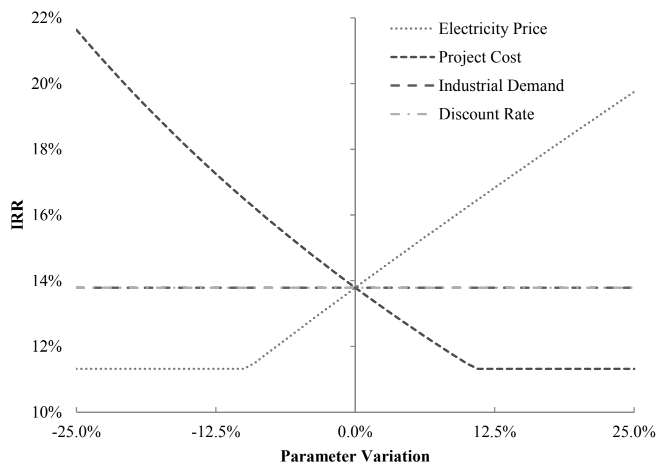

Fig. 8. Sensitivity analysis for IRR with ZIP model 2.

in this case, are system savings, optimal incentive, and IRR. The typical range of such variations for sensitivity analysis depends on how the parameters are normally expected to vary. In the present work, the parameters electricity price, project cost, industrial demand and discount rate, are varied by $\pm25\%$, which is a typical expected range. However, electricity price over variations in the range of $\pm100\%$ have also been considered to represent more extreme case scenarios as discussed in the next section.

D. Risk Analysis using Monte Carlo Simulation

Monte Carlo simulation is performed by perturbing multiple parameters simultaneously, thereby capturing more realistic scenarios than the sensitivity analysis. Each parameter is represented by a random variable with a certain probability distribution function (p.d.f.), assuming that these are all independent, and different samples are generated iteratively until the expected values converge. The objective of Monte Carlo simulation is to find the p.d.f as well as the mean of the system savings and incentive.

The variables adjusted for Monte Carlo simulation are the ZIP models, the industrial demand, project costs, and the electricity price. Since the ZIP model that accurately represents the Ontario system is not known, it is considered a random variable with uniform p.d.f, for models 2 to 10. It is to be noted that ZIP model 1, which represents only constant power loads, always yields an infeasible solution because there are no energy savings from voltage optimization. The industrial demand is also a volatile parameter since deviations can occur from forecast values; therefore, it is modeled considering a uniform p.d.f with its range varying over $\pm15\%$ of its nominal value. Project costs are also assumed to vary $\pm15\%$ around the nominal values, with a uniform p.d.f. Finally, the electricity price is represented by a normal p.d.f with a mean of 43.99 \$/MWh and a standard deviation of 31.74 \$/MWh. As a result, electricity prices exceeding $\pm100\%$ were considered in these studies to simulate more extreme scenarios. To justify the use of a normal p.d.f, the electricity prices from 2002 to 2012

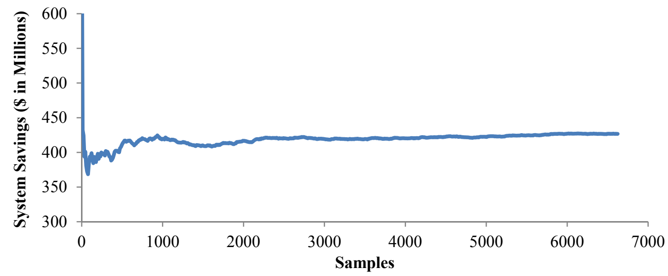

Fig. 9. Variation of the expected system savings in Monte Carlo simulation.

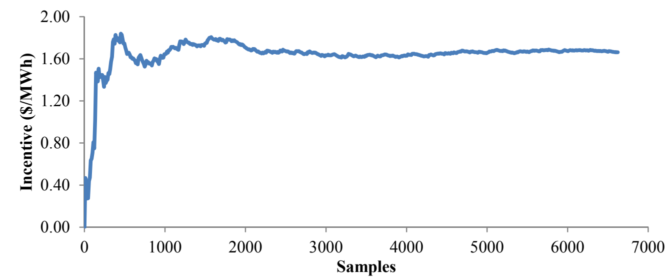

Fig. 10. Variation of the expected incentive in Monte Carlo simulation.

were plotted on a histogram where a normal curve is found to be the most accurate fit.

Monte Carlo simulation is carried out and the convergence of the expected system savings and expected incentive, considering a sample size of 10,000, as in [28], is shown in Fig. 9 and Fig. 10, respectively. Since the parameters of the ZIP model, electricity price, project costs, and industrial demand are modeled as random variables with their respective p.d.f.s, there are a few extreme values at the tails of the probability functions for which no feasible solutions could be found for the given system constraints, as expected; given the low number of infeasible cases, these data points were discarded with no significant impact on the expected values of the output variables. The expected system savings is obtained to be \$427 million, where the highest savings frequency is in the range of \$125 million to \$250 million, having a probability of 20%, as shown in the histogram in Fig. 11. The expected system savings of \$427 million is comparable to the savings obtained in the base case with ZIP model 5 (Table III). The expected incentive is calculated as 1.66 \$/MWh, where the highest incentive frequency occurs at 0 \$/MWh, having a probability of 84%, as shown in the histogram in Fig. 12; the MARR constraint (9) does not allow the rate to go below 0 \$/MWh. It is evident from Monte Carlo simulation that most of the cases do not require an incentive, implying that energy cost savings accrued from voltage optimization are sufficient.

IV. Conclusions

The impact of wide-scale implementation of voltage optimization could be significant on energy reduction; however, it is important to study how much savings and what incentives to distribute in order to help industrial facilities recover the cost

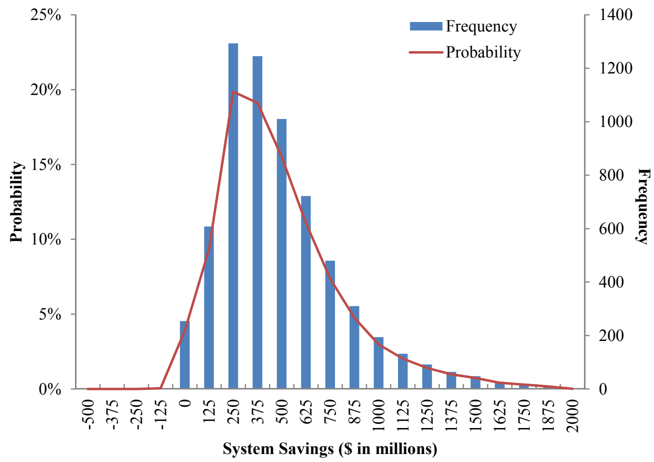

Fig. 11. Monte Carlo simulation output for system savings.

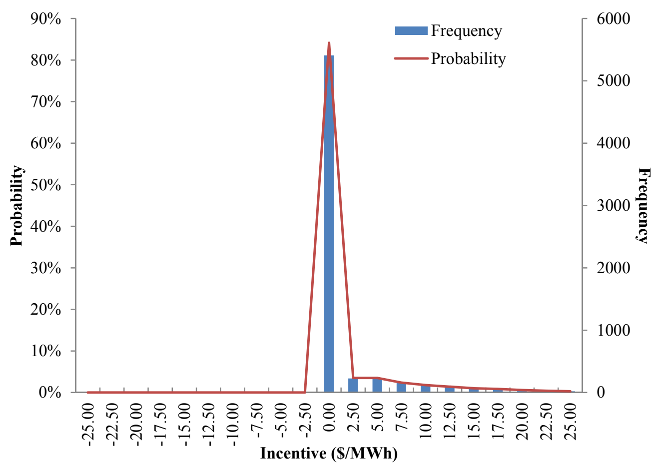

Fig. 12. Monte Carlo simulation output for the incentive.

of a voltage optimization implementation project, while maintaining an IRR above the MARR. In this paper, a novel voltage optimization planning model was proposed to determine the incentive the system planner must offer to industries, while ensuring that the industries adopting this technology accrue an appropriate return on investment. Based on the Ontario system case study, it was concluded that voltage optimization energy savings require little incentive from the system planner in order for investors to meet the MARR.

Since the model has many volatile parameters such as electricity price, industrial demand, project cost and discount rate, sensitivity analyses were performed to observe the impact on the system savings, IRR, and incentive when varying these parameters. Parameters such as electricity price, industrial demand, project cost and discount rate were varied through sensitivity analyses to observe the impact on the system savings, IRR, and incentive. It was noted that increasing the electricity price and industrial demand increases the system savings, whereas the system savings decreased when the discount rate and project cost was increased. In addition, increasing the electricity price reduced the incentive, whereas, when the cost of the project increased, incentives were necessary. It was observed that increasing the electricity price increased the IRR, whereas increasing the cost of the system, decreased the IRR. Monte Carlo simulation was also performed considering simultaneous variation of the ZIP model, industrial demand, electricity price and project cost. The results obtained showed that the expected system savings are comparable to the base case with ZIP model 5; moreover, it showed that most of the cases did not require an incentive.

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